

tidal dissipation

The rotation of the Moon is influenced by solid-body tides and interaction at a liquid-core/solid-mantle boundary. The Lunar Laser Ranging (LLR) data are sensitive to variations in lunar rotation. Analysis of those ranges reveals four dissipation periodicities in the rotation. These signatures can be explained with the combined effects of tide plus core, but not with either alone. The fluid core detection exceeds three times its uncertainty. The inferred core radius has a $1-\sigma$ upper limit of 352 km for iron and up to 374 km if sulfur is present. The tidal dissipation is strong; Q at one month is 37 ± 5 . Q increases for longer periods and is 60 (-15 , $+40$) at one year.

Dynamical evidence for a fluid lunar core has previously been presented [1, 2]. These earlier solutions included three dissipation parameters. New solutions benefit from additional LLR data and an improved gravity field from Doppler tracking of Lunar Prospector [3]. Five dissipation parameters are now solved for. There are several options for dissipation parameters: a core coupling parameter (K/C in [1]), a time delay for tidal distortion of the moments of inertia, and five periodic terms in the rotation angles. Solutions with different combinations of these are compatible (a theory relates K/C and time delay to a series of periodic terms). The solutions in [1, 2] used K/C , time delay, and one periodic term.

When dissipation signatures at five rotation frequencies are solved for, four amplitudes (4 to 263 milliarcs) are detected above the noise. Attempts to explain these results using either tides alone or core alone fail ($> 3\sigma$ discrepancy for the former and 9σ for the latter). A combination of tides and liquid core matches the results well.

The combination of a core plus a frequency-dependent tidal Q is used for interpretation. Frequency dependence is needed since, for the detected coefficients, the most sensitive tidal periods are 1 month, 1 yr, 3 yr and 6 yr. It is assumed that Q follows a power law:

$$Q(\text{tidal period}) = Q(1 \text{ month}) \cdot \left(\frac{\text{Period}}{1 \text{ month}} \right)^{-w}$$

The best match to the detected amplitudes gives $Q(1 \text{ month}) = 37 \pm 5$ and $w = -0.19 \pm 0.13$. The tidal Q is a shallow function of frequency. The annual rotation term for dissipation is mainly a function of Q at 1 yr and does not require the power law for interpretation. The same annual Q of 60 results from the single 4-milliarcs amplitude and the power law match of multiple terms.

The core-mantle torque is interpreted as arising from a

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turbulent boundary layer [4, 5] and topography on the interface. With Yoder's boundary layer theory, approximate estimates of core size can be made, but any topography would make these overestimates. For a liquid iron core the estimated core radius is 335 km, but with concerns for topography, theoretical approximations, and other uncertainties, a $1-\sigma$ upper limit of 352 km is presented. The addition of sulfur to the core would lower the density and raise the core radius. For an Fe-FeS eutectic composition the $1-\sigma$ upper limit would be 374 km.

At the pressure of the lunar core (about 50 kbar) iron melts at 1660°C , but with the addition of sulfur the melting temperature is lowered. The eutectic temperature in the Fe-FeS system is 990°C [6]. Adding nickel can lower the melting temperature another 50°C . The existence of a molten lunar core is compatible with expected central temperatures. Stevenson and Yoder [7] have noted that cooling an Fe-FeS core into the liquid+solid part of the phase diagram can deposit an inner solid core of iron while concentrating the sulfur in the liquid phase. A solid inner core and a liquid outer core is a plausible alternative to a totally liquid core.

A metallic lunar core has long been suspected from several lines of evidence [8, 9], but most of that evidence is compatible with a currently solid or liquid core. The LLR detection of a core through its influence on the lunar rotation can only be explained by a liquid core, but an additional solid inner core is not excluded. That detection now exceeds three times the associated uncertainty.

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